

Beam energy determination in experiments at electron-positron colliders

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ABSTRACT: The review of using of compton backscattering method for determination of the beam energy in collider experiments is given.

KEYWORDS: Compton backscattering; Beam energy calibration; e^+e^- collider.

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1. Introduction

The high accuracy of e^+e^- colliders beam energy determination is crucial for a lot of physical studies:

- particles masses and widths measurements,
- study of interference effects in the cross sections,
- measurements of the cross sections themselves.

For example, the error of the measured Z-boson mass $m_Z = 91187.6 \pm 2.1$ MeV is dominated by the common LEP energy error 1.7 MeV [1]. At the low energy region in order to measure the $e^+e^- \rightarrow \pi^+\pi^-$ cross section below 1 GeV with accuracy about 0.5%, the beam energy should be measured with relative error $\delta E/E \sim 10^{-4}$.

In the simplest case the beam energy can be calculated as

$$E = \frac{B\rho}{\beta c} + \Delta_{cor}, \quad (1.1)$$

where B and ρ are magnetic field and beam radius of curvature, Δ_{cor} is a nonlinear correction. In this case the relative accuracy of the beam energy determination $\delta E/E$ is worse than 10^{-3} . The beam energy can also be determined by measuring of the momentum of particles in collinear events. For example, in special case of the process $e^+e^- \rightarrow \phi(1020) \rightarrow K^+K^-$, the beam energy can be obtained with relative accuracy 5×10^{-5} at the ϕ -meson peak [2] as

$$E = \sqrt{p_K^2 + m_K^2} + \Delta_{cor}, \quad (1.2)$$

where p_K is an average momentum of K^+ and K^- mesons, m_K is the charged kaon mass, Δ_{cor} is a correction due to kaon ionization energy losses and due to emission of real photons. The beam energy can be calibrated using positions of the narrow and precisely measured resonances ($\omega, \phi, \psi, \Upsilon$).

Resonance depolarization (RD) method is the most precise and has relative error of about 10^{-6} [3]. The beam energy determination using RD requires the polarized beam and is based on the coupling between the electron energy and frequency Ω of its spin precession during the motion of the particle in the transverse magnetic field with a revolution frequency ω_s :

$$E = \left(\frac{\Omega}{\omega_s} - 1 \right) \frac{\mu_0}{\mu'} m_e c^2, \quad (1.3)$$

where μ_0/μ' is the ratio of the anomalous and normal parts of the electron magnetic momentum known with a relative accuracy of 2×10^{-10} [1]. The frequency Ω can be obtained through resonant depolarization of the polarized beam due to impact of an external electromagnetic field with a frequency ω_d such that

$$\omega_d \pm k\omega_s = \Omega (k \in \mathbb{Z}). \quad (1.4)$$

Another possibility is the beam energy measurement using Compton back-scattering (CBS) of monochromatic laser radiation on the electron beam.

2. The Compton back-scattering approach

CBS of laser light on electron beams is a well known method of generation of quasimonochromatic energetic photon beams. Let us consider the Compton scattering process in a case when the angle α between initial particles is equal to π and their energies are $\omega_0 \ll m_e \ll E$. Here ω_0 and E are the energies of the initial photon and electron, respectively. The back-scattered photons have the maximal energy, and the energy spectrum of the scattered photons has a sharp edge at the maximal energy:

$$\omega_{max} = \frac{E^2}{E + m_e^2/4\omega_0}. \quad (2.1)$$

If one measures ω_{max} , then the electron energy can be calculated:

$$E = \frac{\omega_{max}}{2} \left[1 + \sqrt{1 + \frac{m_e^2}{\omega_0 \omega_{max}}} \right]. \quad (2.2)$$

The measurement procedure is as follows. The laser light is put in collision with the electron or positron beams, and the energy of the back-scattered photons is precisely measured using the High

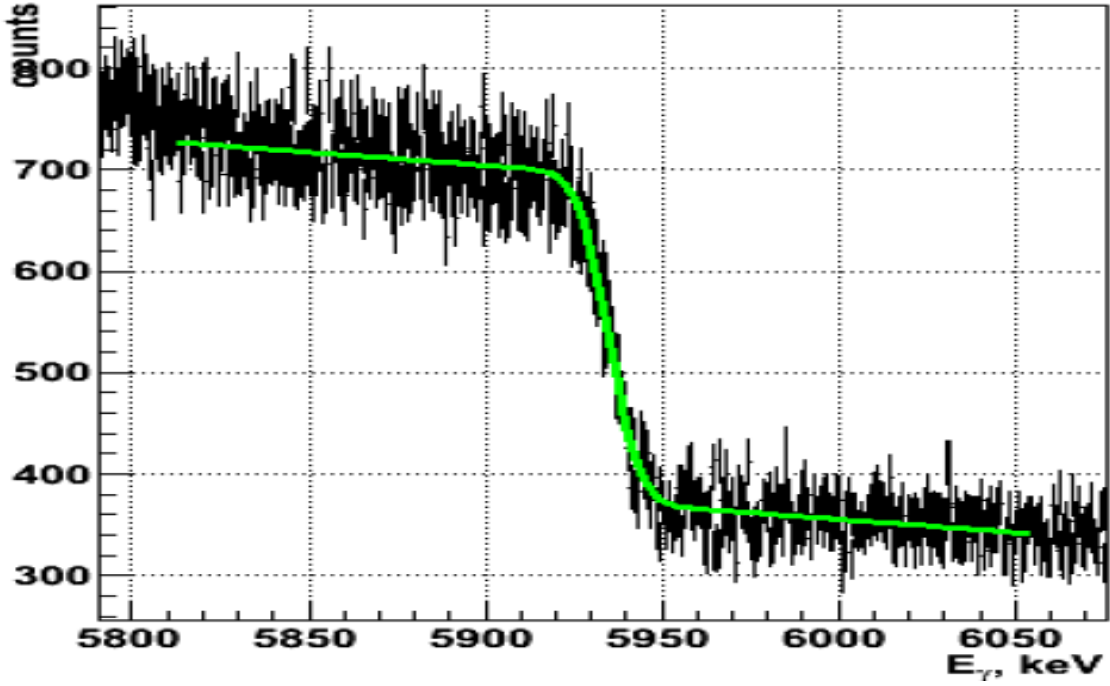


Figure 1. The measured edge of the scattered photons energy spectrum at BEPC-II. Line is the fit result.

Purity Germanium (HPGe) detector. The maximal energy of the scattered photons is determined by fitting the abrupt edge in the energy spectrum by the erfc-like function (figure 1). The beam energy E is calculated from the maximum energy ω_{max} using eq. (2.2). CBS method provides rather high accuracy, a possibility of measurements in a wide energy region, allows to measure beam energy during data taking.

This approach was developed and experimentally proved in ref. [4–12]. First measurement of the beam energy $E \approx 1.3$ GeV at storage ring of Taiwan Light Source with accuracy $\delta E/E \sim 10^{-3}$ was reported in ref. [6]. The accuracy of the measurements was improved at SR sources BESSY-I and BESSY-II. The relative accuracies of energy measurement of about 2×10^{-4} and 3×10^{-5} was achieved for the beam energy of 800 MeV and 1.7 GeV at the BESSY-I and BESSY-II storage rings respectively [7, 8]. The accuracies was proved by comparison with results of RD method. In collider experiments, the CBS method was applied at VEPP-4M [10] and the $\tau - charm$ factory BEPC-II [11] for measurement of beam energy 1 – 2 GeV, and at VEPP-2000 below 1 GeV [12].

3. Beam energy measurement system for CBS method.

A beam energy measurement system (BEMS) includes:

- laser and optical system to provide initial photons and their transportation,
- laser-to-vacuum insertion system which provides insertion of the laser beam into the vacuum chamber of collider,
- HPGe detector to measure backscattered photons spectrum,

Table 1. Radiative sources of γ -quanta which can be used for the HPGe detector calibration.

Source	E_γ , keV
^{208}Tl	583.191 ± 0.002
^{137}Cs	661.657 ± 0.003
^{60}Co	1173.237 ± 0.004
^{60}Co	1332.501 ± 0.005
^{208}Tl	2614.553 ± 0.013
$^{16}\text{O}^*$	6129.266 ± 0.054

- data acquisition system,
- data processing.

3.1 HPGe detector

The purpose of a HPGe detector is to convert gamma rays into electrical impulses which can be used with suitable signal processing, to determine their energy and intensity. A HPGe detector is a large germanium diode operated in the reverse bias mode. At a suitable operating temperature (normally $\simeq 100$ K), the barrier created at the junction reduces the leakage current to acceptably low values. Thus an electric field can be applied that is sufficient to collect the charge carriers liberated by the ionizing radiation.

Commercially available coaxial HPGe detector with diameter 5 – 6 cm and height 5 – 7 cm has energy resolution $\delta\omega/\omega \sim 10^{-3}$ and can measure the γ -quanta energy below 10 MeV. The detector is connected to the multi-channel analyzer (MCA).

The statistical accuracy of beam energy measurement of about $5 \times (10^{-4} - 10^{-5})$ can be achieved in a reasonable time (about 1 hour). The systematic accuracy is mostly determined by absolute calibration of the detector, which could be done in the photon energy range up to ~ 10 MeV by using the γ -active radionuclides (table 1).

3.2 Laser

Laser is the source of initial photons. The main requirements to it are:

- the single generation line,
- high stability of parameters,
- easy maintenance,
- the choice of the wavelength should provide the maximal energy ω_{max} in the range from 0.2 to 6.0 MeV (figure 2), for which HPGe detector can be calibrated using γ -active radionuclides (table 1).

At the low energy region $E < 0.5$ GeV the solid state laser with wavelength $\lambda \approx 1.065$ μm can be used. At VEPP-2000 to measure the beam energy below 1 GeV the PL3 CO laser from Edinburgh Instruments with power of 2 W at $\lambda \approx 5.3$ μm is used [12]. The GEM Selected 50TM CO₂ lasers from Coherent, Inc with $\lambda \approx 10$ μm and power of 25 W are implemented to determine the beam energy $1 < E < 2$ GeV at VEPP-4M and BEPC-II colliders [10, 11].

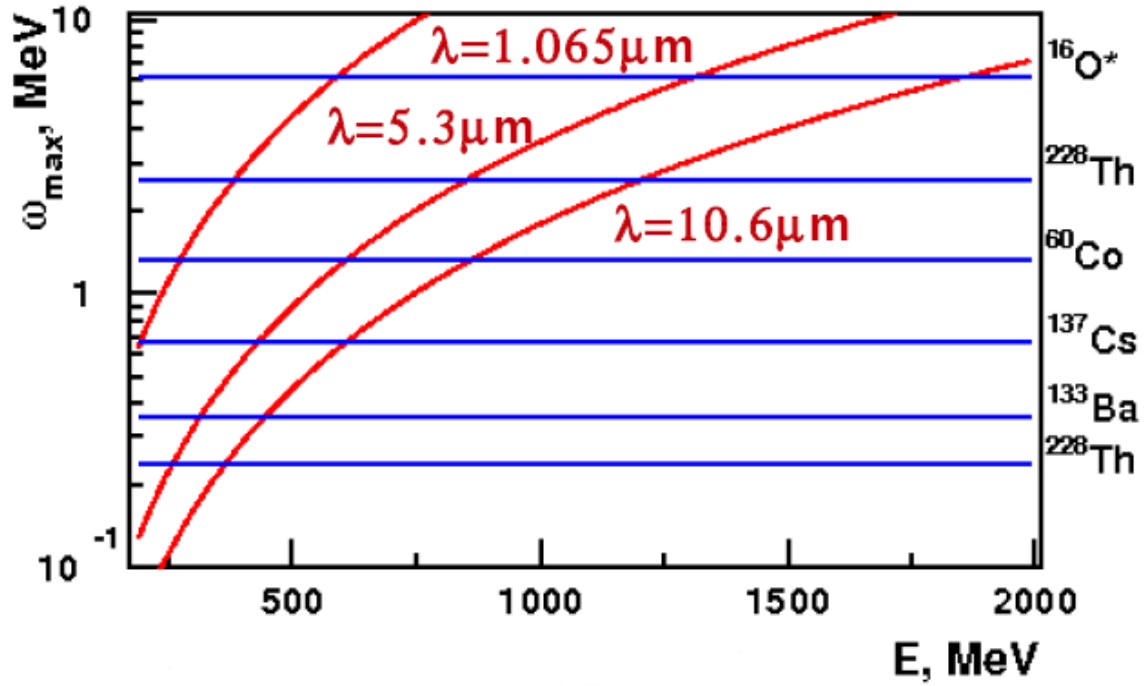


Figure 2. Relation between ω_{max} and E for different laser wavelengths. The solid lines are the energies of γ -active radionuclide reference lines for the HPGc calibration.

3.3 Laser-to-vacuum insertion system

The insertion of the laser beam into the collider vacuum chamber is performed using the laser-to-vacuum insertion system. The system is the special stainless steel vacuum chamber with a entrance viewport and water cooled copper mirror (figure 3) [11, 13]. The system provides extra-high vacuum – pressure of residual gas less then 5×10^{-10} Torr. The viewport transfers laser light and some amount of synchrotron radiation (SR) light to monitor the beam position. In the vacuum chamber, the laser beam is reflected through an angle of 90° by the copper mirror. The mirror can be turned by bending the vacuum flexible bellows, so the angle between the mirror and the laser beam can be adjusted as necessary. SR photons heat the mirror. The extraction of heat is provided by a water cooling system. After back-scattering, the photons return to the mirror, pass through it, leave the vacuum chamber, and are detected by the HPGc detector. Note, the copper mirror protects the viewport against high power SR due to low reflectivity of high energy photons (less than 1%) from a metallic surface.

There are two types of viewports. The first one is based on GaAs mono-crystal plate with diameter of 50.8 mm and thickness of 3 mm. The second is based on ZnSe polycrystal plate with diameter of 50.8 mm and thickness of 8 mm. Both viewports are manufactured using similar technology [11, 14] and provide:

1. baking out the vacuum system up to 250°C ,
2. extra-high vacuum,

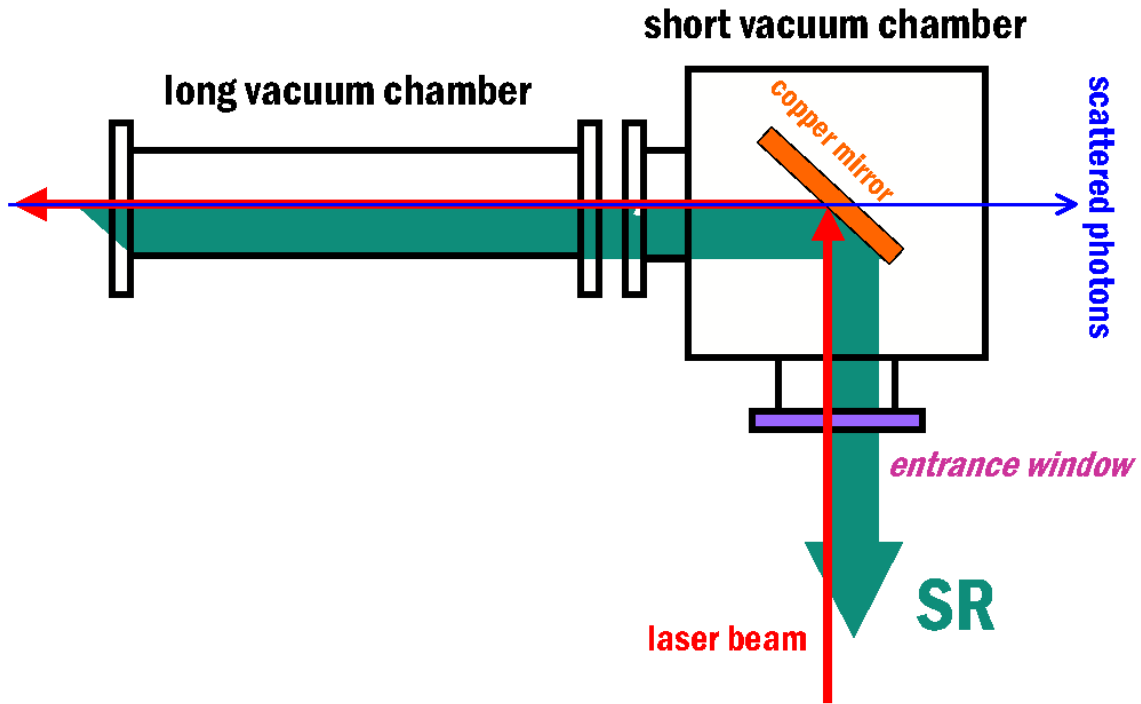


Figure 3. Simplified schematic of the laser-to-vacuum insertion assembly.

3. transmission spectrum from 0.9 up to 18 μm (GaAs viewport) and from 0.45 to 20 μm (ZnSe viewport).

The advantage of ZnSe viewport is that it is transparent for the visible part of SR light. This makes the BEMS adjusting more convenient.

3.4 Optical system.

The optical system includes the following main units (figure 4):

- Two ZnSe lenses which focus a laser beam at $e - \gamma$ interaction region.
- The mirror which reflects the laser beam to a viewport of insertion system. It is installed on a special support that allows precise vertical and horizontal angular alignment by using stepping motors.

The optical elements of the system are aligned using the SR light of the electron beam in such a way that the SR light comes to the laser output window.

3.5 Data acquisition system.

The BEMS data acquisition system is shown in figure 5. The MCA digitizes the signal from the HPGe detector and produces the energy spectrum. It is connected to a Windows PC. All spectra processing, monitoring and control over the devices involved in the BEMS is concentrated in another PC, under the control of Linux.

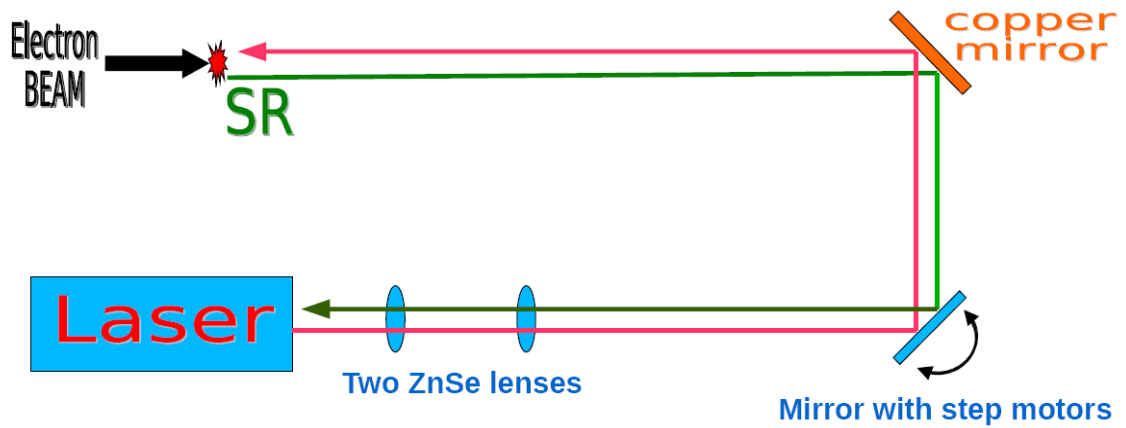


Figure 4. Simplified schematic of the optical system.

The data acquisition procedure is as follows. The HPGe detector measurements are read every few seconds, and the detector counting rate is calculated. If the requested acquisition time has elapsed, or if conditions of the spectrum acquisition changed sufficiently, the current spectrum is saved to a file and the next spectrum acquisition cycle is launched. Simultaneously, another process periodically requests information from collider database and writes the collider parameters, such as beam currents, lifetimes, etc to the file.

The data for the HPGe detector calibration – peaks of the γ sources and peaks of the precise calibration pulser BNC model BP-5 with integrated nonlinearity ± 15 ppm and jitter ± 10 ppm are accumulated simultaneously with scattered photons. Generator signals are put to the preamplifier with 12 different amplitudes covering the range of MCA and frequency of about 40 Hz. The pulse shape is set in such a way that it is similar to the shape of the signal from a γ -quantum.

After finishing the spectrum acquisition cycle, another program processes the spectrum; it calibrates the energy scale, finds the Compton edge, and calculates the beam energy. The beam energy is written into the database.

During data taking, mirror are adjusted automatically to provide maximal photon/electron interaction efficiency, using the feedback from the detector counting rate. The processing of the beam energy measurement is fully automated.

3.6 Data processing.

The processing of the spectrum (figure 6) includes calibration of the energy scale, Compton edge fitting and determination of the beam energy.

The goal of the HPGe detector calibration is to obtain the coefficients needed for conversion of the MCA counts into the corresponding energy deposition, measured in units of keV, as well as to determine the parameters of the detector response function. The following response function is

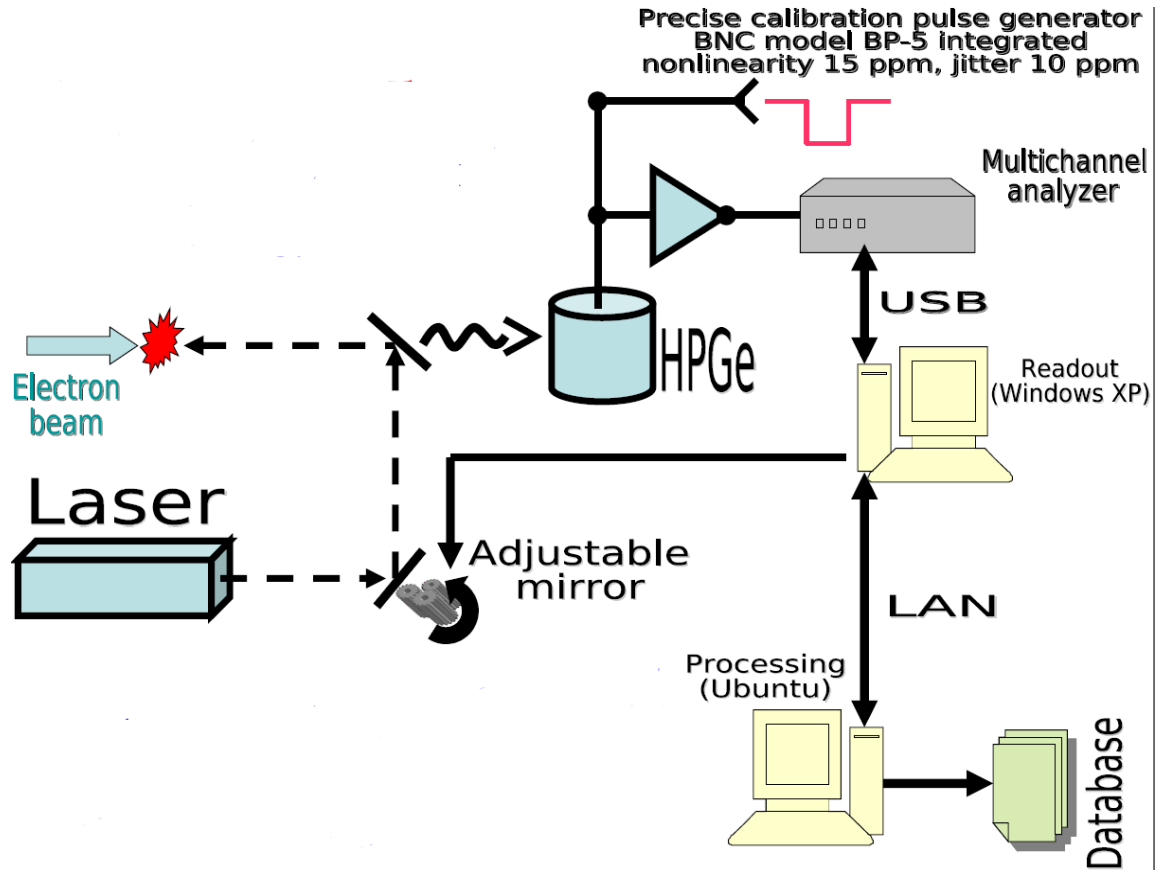


Figure 5. Layout of data acquisition system.

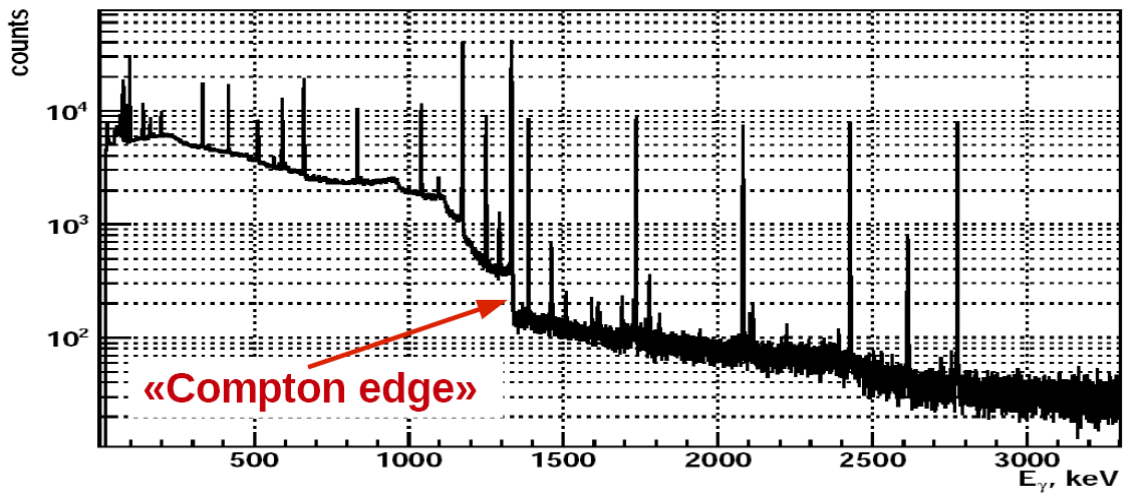


Figure 6. The energy spectrum detected by HPGe detector at VEPP-2000. Peaks correspond to the calibration generator and monochromatic γ -radiation sources.

used (figure 7):

$$f(x, x_0) = M \cdot \begin{cases} \exp\left\{-\frac{(x-x_0)^2}{2\sigma^2}\right\}, & 0 < x - x_0 < +\infty, \\ C + (1 - C) \exp\left\{\frac{(x-x_0)^2}{2(K_0\sigma)^2}\right\}, & -K_0K_1\sigma < x - x_0 \leq 0, \\ C + (1 - C) \exp\left\{K_1\left(\frac{x-x_0}{K_0\sigma} + \frac{K_1}{2}\right)\right\}, & -\infty < x - x_0 \leq -K_0K_1\sigma, \end{cases} \quad (3.1)$$

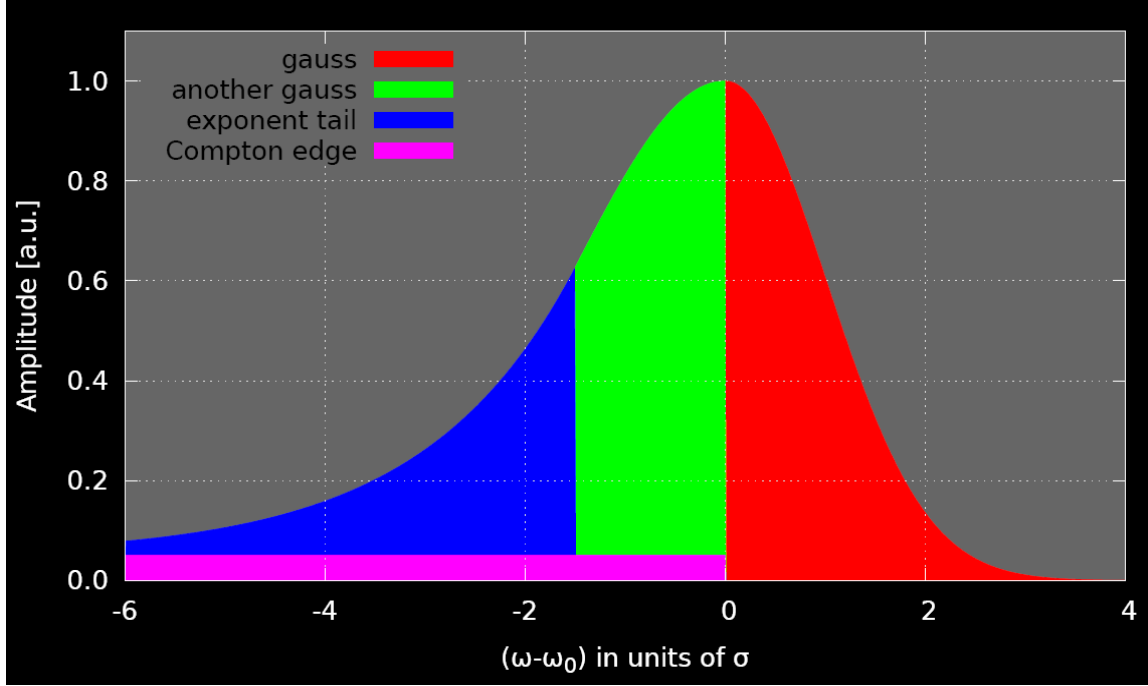


Figure 7. HPGe detector response function.

where M is normalization, x_0 is the position of the maximum, σ and $K_0\sigma$ are RMS of the Gaussian distribution to the right and to the left of the x_0 , respectively, C is responsible for the small-angle Compton scattering of γ -quanta in the passive material between the source and the detector, K_1 is an asymmetry parameter.

The calibration procedure is as follows [11, 12]:

1. Peak search and identification of the calibration lines.
2. The calibration peaks are fitted by the sum of response function and background (figure 8).
3. Using generator data the nonlinearity of MCA scale is obtained.
4. Using the results of the isotope peak approximation, the energy dependence of the response function parameters σ , K_0 , K_1 and C are determined.

The width of backscattered photons spectrum edge depends on the HPGe detector resolution and the electron beam energy spread. The spectrum edge is fitted by the function, which takes into account the «pure» edge shape, detector response function, energy spread of scattered photons due to the energy distribution of the collider beam. The edge position ω_{max} and the photons energy spread σ_ω are obtained from the fit. The beam energy E and energy spread σ_E are calculated from ω_{max} and σ_ω .

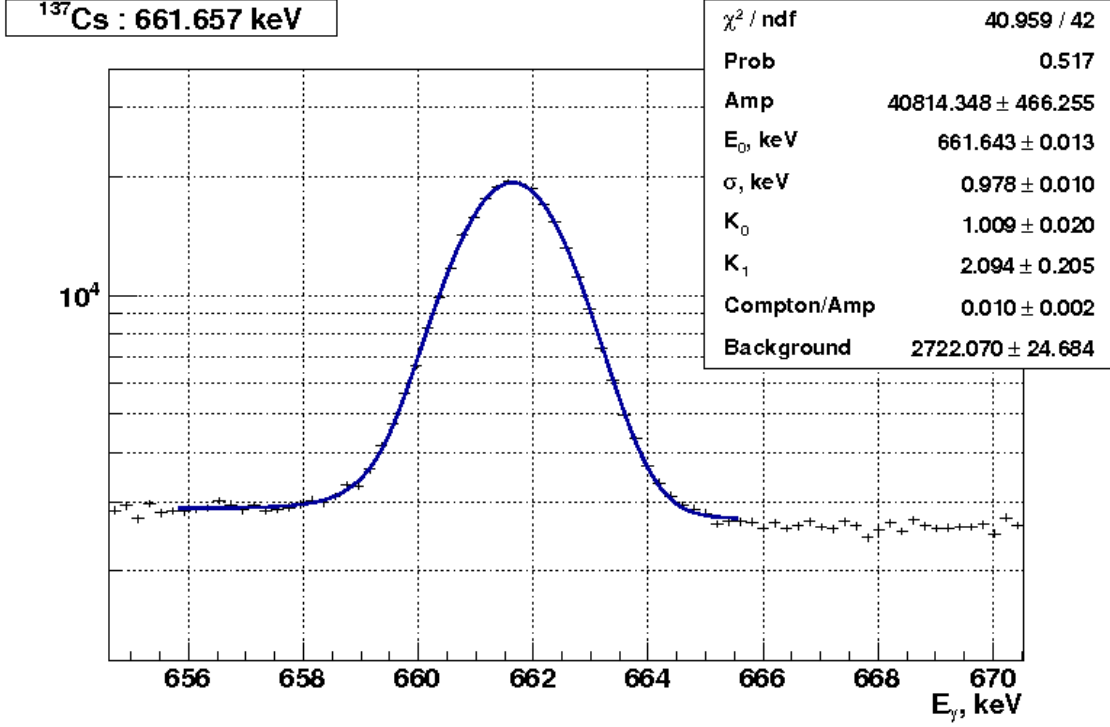


Figure 8. The fit to the ^{137}Cs 661 keV peak.

4. Performance of BEMS at collider experiments.

4.1 BEMS at VEPP-4M.

The accurate beam energy determination is essential for precise mass measurements of J/ψ , ψ' , $\psi(3770)$, D mesons and τ -lepton in experiments with the KEDR detector [15] at the electron-positron collider VEPP-4M [16]. The RD technique provides precise instantaneous energy calibration. CBS method allows continuous on-line monitoring of the beam energy. The layout of BEMS is shown at Figure 9. The laser and electron beams interact in the straight section of the collider's ring near KEDR detector. Since the electron and positron beams circulate in the same vacuum chamber in the same magnetic field their energies are identical. The source of initial photons is CO_2 laser and $\omega_{\text{max}} = 2 - 7$ MeV for $E = 1 - 2$ GeV.

The test of CBS method accuracy was performed by comparison of precisely known J/ψ resonance mass 3096.916 ± 0.011 [1] MeV with its value obtained using BEMS (figure 10). The mass difference was found to be $\Delta m = 1.2 \pm 14.7$ keV. Deviation of the measured beam energy from the actual value can be estimated as $\Delta E = \Delta m/2 = 0.6 \pm 17.4$ keV, then relative accuracy of the beam energy determination is $\delta E/E = 5 \times 10^{-6}$.

Direct comparison of CBS and RD methods was performed at the beam energy $E = 1553.4$ MeV and $E = 1884$ MeV. At the beam energy 1553.4 MeV there was no systematical bias between RD and CBS results within statistical errors of the CBS measurements (figure 11) and $\delta E/E = 1.3 \times 10^{-5}$. At the beam energy 1884 MeV the difference between RD and CBS measurements was 13 ± 38 keV, and $\delta E/E = 2 \times 10^{-5}$. Using results of the tests the relative error of the CBS

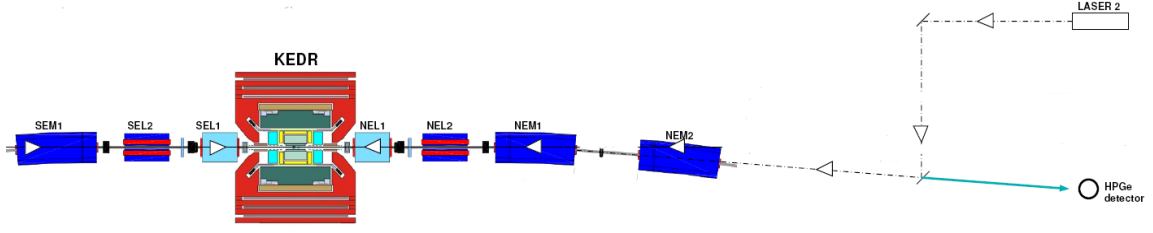


Figure 9. Layout of VEPP-4M beam energy measurement system.

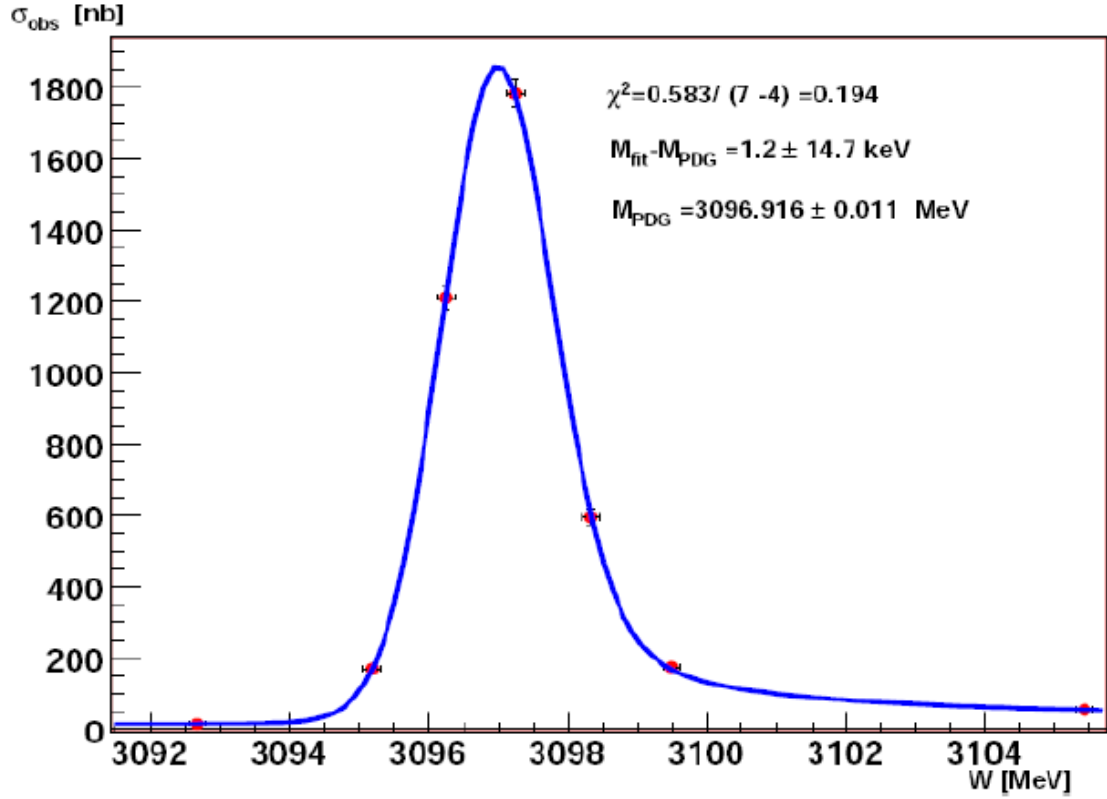


Figure 10. Fit to the J/ψ at VEPP-4M.

measurements at VEPP-4M can be estimated as 10^{-5} .

4.2 BEMS at BEPC-II.

The BEMS (figure 12) is located at the north interaction point of BEPC-II collider [17], while the BESIII detector [18] is installed at the south interaction point. This location provides measurement of the electron and positron beams energy by the same HPGe detector. The laser and electron (positron) beams interact in the straight sections of the collider's rings beyond the R2IAMB (R1IAMB) dipole magnets. The source of initial photons is CO₂ laser. The laser beam is directed to either the electron or positron beams. The energy of the electron and positron beams are mea-

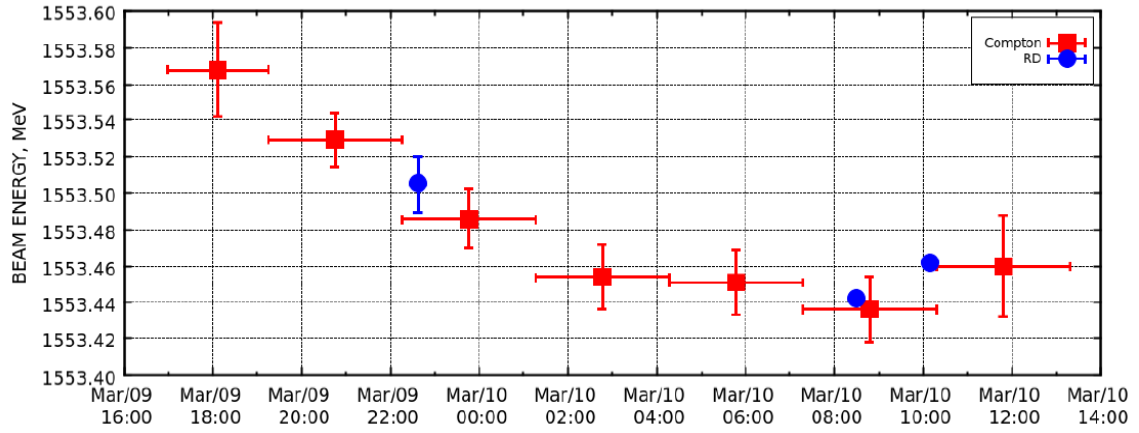


Figure 11. Comparison of RD (dots) and CBS (squares) measurements at the beam energy $E = 1553.4$ MeV.

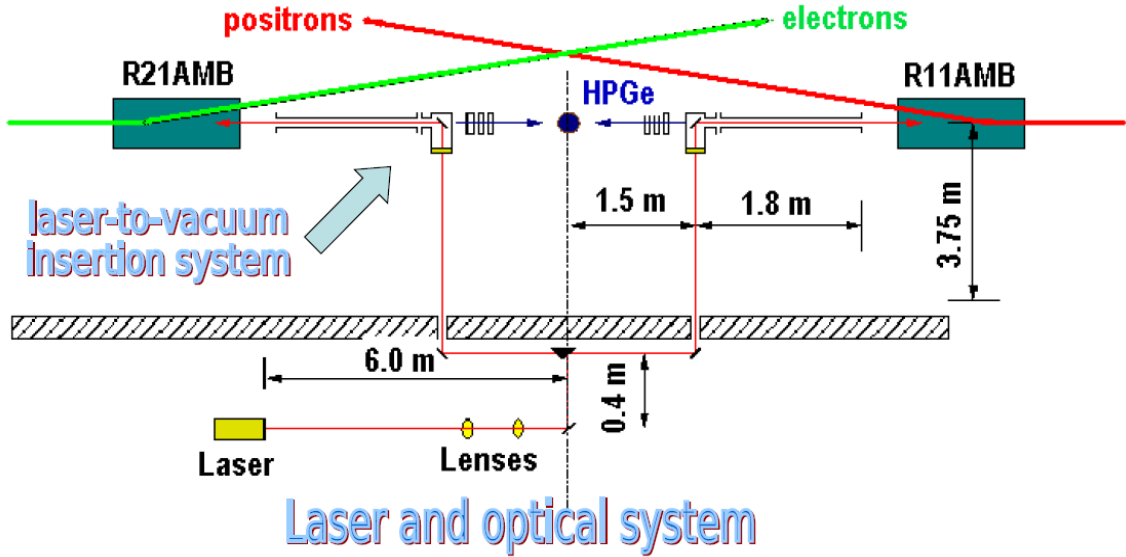


Figure 12. Layout of BEPC-II beam energy measurement system.

sured one after another, in turn. The beam energy in the south interaction point is calculated using measured energy, tacking into account the energy losses due to synchrotron radiation.

Since the HPGe detector is located near the collider's beam pipes, background due to beam loss is extremely high. In order to protect the HPGe detector from background, it is surrounded by 5 cm of lead on the sides, by 1.5 cm of iron below, and by 5 cm of lead above. The detector is also shielded by 10 cm of paraffin on all sides. Since the main background comes from the beam direction, an additional 11 cm of lead is installed in these directions. Another 10 cm of lead can be inserted into the beam using movable stages to shield from the beam direction that is not being measured and moved out when the beam is being measured.

The systematical accuracy was studied by comparison of the well known mass of the J/ψ

Table 2. The deviations of the beam energy from the actual value at BEPC-II.

Scan	ΔE , keV	$\delta E/E$
$J/\psi(2010)$	74 ± 57	6×10^{-5}
$\psi'(2010)$	118 ± 79	7×10^{-5}
$\psi'(2009)$	1 ± 36	2×10^{-5}

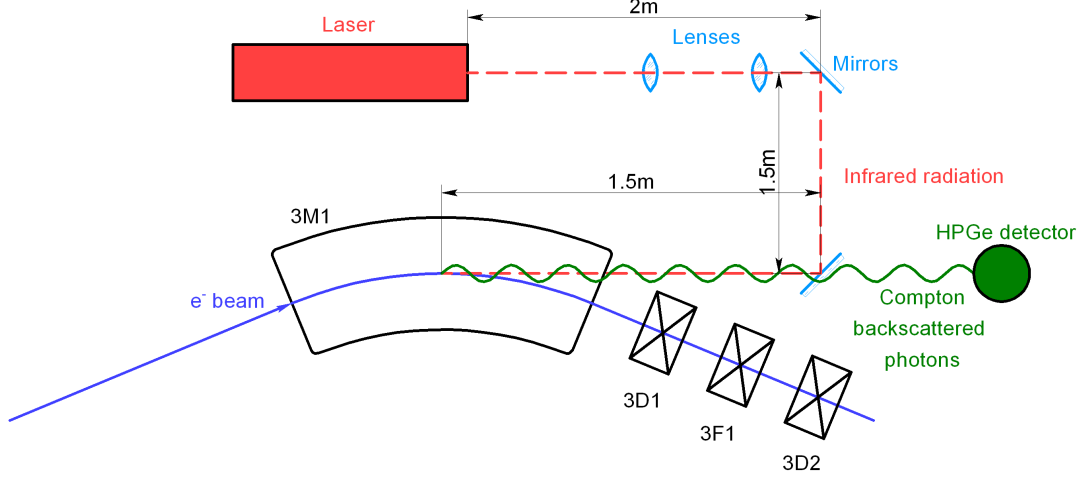


Figure 13. Layout of VEPP-2000 beam energy measurement system.

and ψ' resonance with its value obtained using the BEMS. One comparison was done after the BEMS was put to operation in 2009 and another during energy scan near the τ pair threshold in 2010 [11, 19]. The results are presented in table 2. The relative accuracy of the beam energy determination can be estimated as 5×10^{-5} .

4.3 BEMS at VEPP-2000.

At VEPP-2000 the interaction of laser photons with electrons occurs inside bending magnet ($\rho = 140$ cm) at the curvilinear part of the orbit (figure 13). The source of initial photons is CO laser such that $\omega_{max} = 0.2 - 2$ MeV for the beam energy $E < 1$ GeV. In this case the spectrum of scattered photons (figure 14) differs from that expected from by the Klein-Nishina cross section and scattering kinematics of free electrons [20]. The interference of scattered photons is observed in the energy spectrum. The systematic error of the beam energy determination was tested by comparison with a measurement using the resonance depolarization method at the beam energy 458 and 509 MeV and is estimated as 6×10^{-5} .

5. CBS method for the beam energy above 2 GeV.

Application of the CBS method is constrained by the requirement $\omega_{max} \lesssim 10$ MeV, i.e. by the laser wavelength. The BEMS for the beam energy above 2 GeV can be based on the far infrared laser (FIR) with wavelength $\lambda \sim 100$ μm . Such a device FIRL 100 is manufactured by Edinburgh

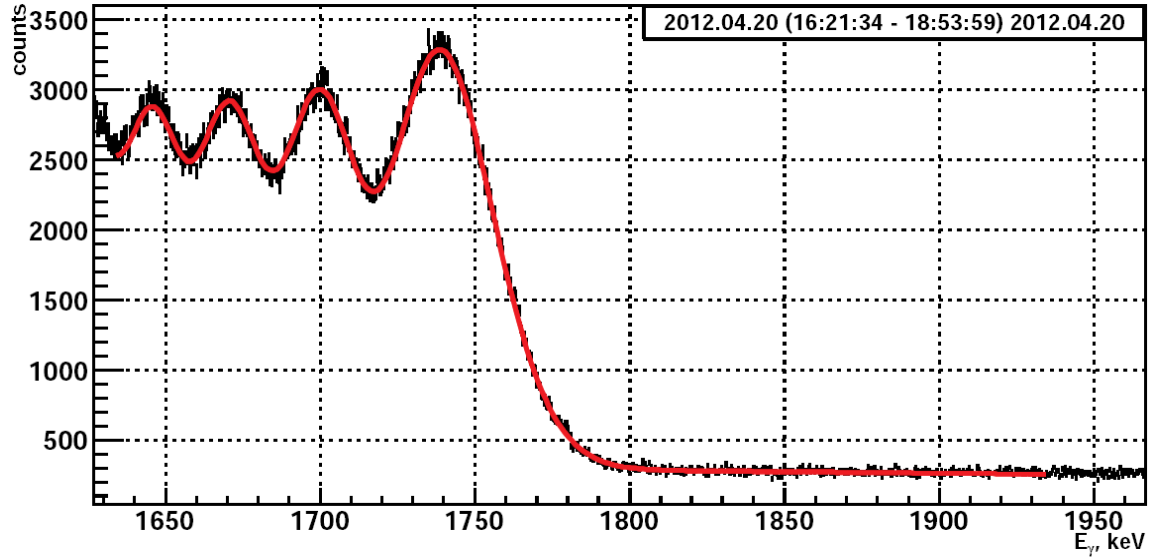


Figure 14. The edge of energy spectrum with the fit at VEPP-2000.

Instruments with maximal power of 150 mW at $\lambda \approx 119$ and $184 \mu\text{m}$. For these wavelength the $\omega_{\text{max}} \approx 0.2 - 10 \text{ MeV}$ at the beam energy $E = 2 - 8 \text{ GeV}$. At SPring-8 synchrotron radiation facility the MeV photons was produced by the CBS of the FIR laser radiation with $\lambda = 119 \mu\text{m}$ and power of 1.6 W at the 8 GeV electron beam [21].

6. Conclusion.

The CBS method is effective tool for collider energy measurement and monitoring. The method can be applied for the electron beam energy below 2 GeV. The relative accuracy of the method is $10^{-4} - 10^{-5}$. For determination of the beam energy from 2 to 8 GeV the FIR laser can be used, but this requires additional studies.

Acknowledgments

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